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THE DYNAMICAL DIPOLE RADIATION IN DISSIPATIVE COLLISIONS WITH EXOTIC BEAMS

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Heavy Ion Collisions (HIC) represent a unique tool to probe the in-medium nuclear interaction in regions away from saturation. In this work we present a selection of reaction observables in dissipative collisions particularly sensitive to the isovector part of the interaction, i.e. to the symmetry term of the nuclear Equation of State (EoS). At low energies the behavior of the symmetry energy around saturation influences dissipation and fragment production mechanisms. We will first discuss the recently observed Dynamical Dipole Radiation, due to a collective neutron-proton oscillation during the charge equilibration in fusion and deep-inelastic collisions. We will review in detail all the main properties, yield, spectrum, damping and angular distributions, revealing important isospin effects. Reactions induced by unstable ^{132}Sn beams appear to be very promising tools to test the sub-saturation Isovector EoS. Predictions are also presented for deep-inelastic and fragmentation collisions induced by neutron rich projectiles. The importance of studying violent collisions with radioactive beams at low and Fermi energies is finally stressed.

Keywords: Dinamical Dipole, Charge Equilibration, Symmetry Energy, Isospin Transport

1. Introduction

The symmetry energy E_{sym} appears in the energy density $\epsilon(\rho,\rho_3) \equiv \epsilon(\rho) + \rho E_{sym}(\rho_3/\rho)^2 + O(\rho_3/\rho)^4 + ..$, expressed in terms of total ($\rho = \rho_p + \rho_n$) and isospin ($\rho_3 = \rho_p - \rho_n$) densities. The symmetry term gets a kinetic contribution directly from basic Pauli correlations and a potential part from the highly controversial isospin dependence of the effective interactions [1]. Both at sub-saturation and supra-saturation densities, predictions based of the existing many-body techniques diverge rather widely, see [2]. We take advantage of new opportunities in theory (development of rather reliable microscopic transport codes for HIC) and in experiments (availability of very asymmetric radioactive beams, improved possi-

bility of measuring event-by-event correlations) to present results that are severely constraining the existing effective interaction models. We will discuss dissipative collisions in the low energy range, from just above the Coulomb barrier up to about hundred $AMeV$. In this way we can probe in detail the symmetry energy in dilute matter. The transport codes are based on mean field theories, with correlations included via hard nucleon-nucleon elastic and inelastic collisions and via stochastic forces, selfconsistently evaluated from the mean phase-space trajectory, see [1,3,4,5]. Stochasticity is essential in order to get distributions as well as to allow the growth of dynamical instabilities. The isovector part of the EoS has been tested systematically by using two different behaviors of the symmetry energy below saturation: one ($Asysoft$) where it is a smooth decreasing function towards low densities, and another one ($Asystiff$) where we have a rapid decrease, [1,6].

2. The Prompt Dipole γ-Ray Emission

The possibility of an entrance channel bremsstrahlung dipole radiation due to an initial different N/Z distribution was suggested at the beginning of the nineties [7,8], largely inspired by D.M.Brink discussions. At that time a large debate was present on the disappearing of *Hot Giant Dipole Resonances* in fusion reactions. Brink was suggesting the simple argument that a GDR needs time to be built in a hot compound nucleus, meanwhile the system will cool down by neutron emission and the GDR photons will show up at lower temperature. The natural consequence suggested in ref. [7] was that we would expect a new dipole emission, in addition to the statistical one, if some pre-compound collective dipole mode is present. After several experimental evidences, in fusion as well as in deep-inelastic reactions [9,10,11,12,13] we have now a good understanding of the process and stimulating new perspectives from the use of radioactive beams.

During the charge equilibration process taking place in the first stages of dissipative reactions between colliding ions with different N/Z ratios, a large amplitude dipole collective motion develops in the composite dinuclear system, the so-called dynamical dipole mode. This collective dipole gives rise to a prompt γ-ray emission which depends: i) on the absolute value of the intial dipole moment

$$\begin{aligned} D(t=0) = \frac{NZ}{A}\,|R_Z(t=0) - R_N(t=0)| = \\ \frac{R_P + R_T}{A} Z_P Z_T \left| (\frac{N}{Z})_T - (\frac{N}{Z})_P \right|, \end{aligned} \tag{1}$$

being $R_Z = \frac{\Sigma_i x_i(p)}{Z}$ and $R_N = \frac{\Sigma_i x_i(n)}{N}$ the center of mass of protons and of neutrons respectively, while R_P and R_T are the projectile and target radii; ii) on the fusion/deep-inelastic dynamics; iii) on the symmetry term, below saturation, that is acting as a restoring force.

A detailed description is obtained in a microscopic approach based on semiclassical transport equations, of Landau-Vlasov type, [16], where mean field and two-body

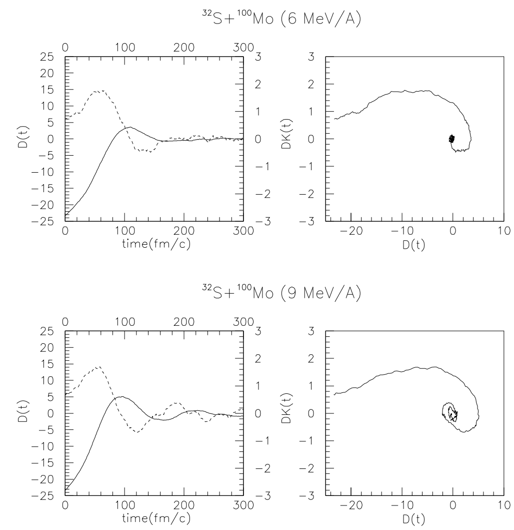

Fig. 1. The time evolution of the dipole mode in $r-$space $D(t)$ (solid lines) and $p-$space $DK(t)$ (dashed lines, in fm^{-1}) and the correlation $DK(t)-D(t)$ at incident energy of $6AMeV$ and $9AMeV$ for $b=2fm$.

collisions are treated in a self-consistent way, see details in [17]. Realistic effective interactions of Skyrme type are used. The numerical accuracy of the transport code has been largely improved in order to have reliable results also at low energies, just above the threshold for fusion reactions [18,19]. The resulting physical picture is in good agreement with quantum Time-Dependent-Hartree-Fock calculation [20]. In particular we can study in detail how a collective dipole oscillation develops in the entrance channel [19].

First, during the *approaching phase*, the two partners, overcoming the Coulomb barrier, still keep their own response. Then a *dinuclear phase* follows, where the relative motion energy, due to the nucleon exchange, is converted in thermal motion and in the collective energy of the dinuclear mean field. In fact the composite system is not fully equilibrated and manifests, as a whole, a large amplitude dipole collective motion. Finally thermally equilibrated reaction products are formed, with consequent statistical particle/radiation emissions.

We present here some results for the ^{32}S $+^{100}$Mo (N/Z asymmetric) reaction at 6 *and* 9 $AMeV$, recently studied vs. the "symmetric" ^{36}S $+^{96}$Mo counterpart in ref.[13]. In Fig.1 (left columns) we draw the time evolution for $b=2fm$ of the dipole moment in the r-space (solid lines), $D(t)=\frac{NZ}{A}(R_Z-R_N)$ and in $p-$space (dashed lines), $DK(t)=(\frac{P_p}{Z}-\frac{P_n}{N})$, with P_p (P_n) center of mass in momentum space for protons (neutrons), is just the canonically conjugate momentum of the $D(t)$ coordinate, i.e. as operators $[D(t),DK(t)]=i\hbar$ see [19,20,21]. On the right hand side columns we show the corresponding correlation $DK(t)-D(t)$ in the phase

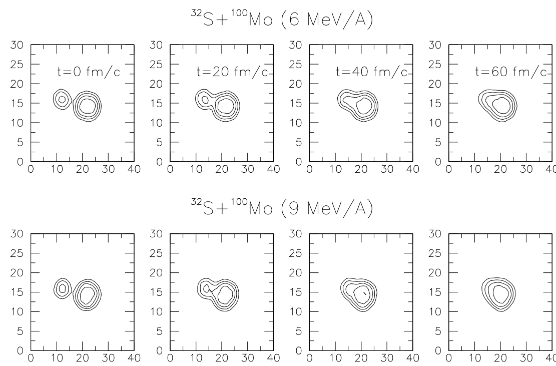

Fig. 2. Density plots of the neck dynamics for the ^{32}S $+^{100}$Mo system at incident energy of $6AMeV$ and $9AMeV$.

space. We choose the origin of time at the beginning of the *dinuclear* phase. The nice "spiral-correlation" clearly denotes the collective nature of the mode. ¿From Fig.2 we note that the "spiral-correlation" starts when the initial dipole moment $D(t=0)$, the geometrical value at the touching point, is already largely quenched. This is the reason why the dinucleus dipole yield is not simply given by the "static" estimation but the reaction dynamics has a large influence on it.

A clear energy dependence of the dynamical dipole mode is evidenced with a net increase when we pass from $6AMeV$ to $9AMeV$. A possible explanation of this effect is due to the fact that at lower energy, just above the Coulomb barrier, a longer transition to a dinuclear configuration is required which hinders the isovector collective response. From Fig.2 a slower dynamics of the neck during the first $40fm/c - 60fm/c$ from the touching configuration is observed at 6 $AMeV$. When the collective dipole response sets in the charge is already partially equilibrated via random nucleon exchange.

The bremsstrahlung spectra shown in Fig.3 support this interpretation.

In fact from the dipole evolution given from the Landau-Vlasov transport we can directly apply a bremsstrahlung *("bremss")* approach [21] to estimate the "direct" photon emission probability ($E_\gamma = \hbar\omega$):

$$\frac{dP}{dE_\gamma} = \frac{2e^2}{3\pi\hbar c^3 E_\gamma}|D''(\omega)|^2, \qquad (2)$$

where $D''(\omega)$ is the Fourier transform of the dipole acceleration $D''(t)$. We remark that in this way it is possible to evaluate, in *absolute* values, the corresponding pre-equilibrium photon emission. In the same Fig.3 we show statistical GDR emissions from the final excited residue. We see that at the higher energy the prompt emission represents a large fraction of the total dipole radiation.

In the Table we report the present status of the Dynamical Dipole data, obtained from fusion reactions. We note the dependence of the extra strength on the interplay between initial dipole moment and initial mass asymmetry [15]: this clearly indicates

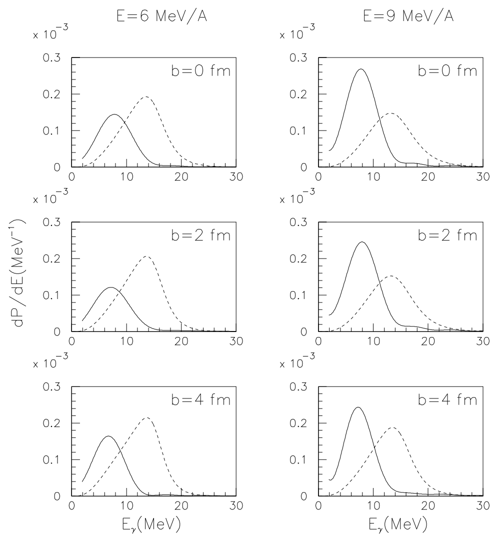

Fig. 3. The bremsstrahlung spectra for the ^{32}S +^{100}Mo system at incident energy of $6AMeV$ and $9AMeV$ (solid line) and the first step statistical spectrum (dashed line) for three impact parameters.

Table 1. *The percent increase of the intensity in the linearized γ-ray spectra at the compound nucleus GDR energy region (the energy integration limits are given in the parenthesis), the compound nucleus excitation energy, the initial dipole moment $D(t=0)$ and the initial mass asymmetry Δ for each reaction.*

Reaction	Increase (%)	E*(MeV)	$D(t=0)$ (fm)	Δ	Ref
^{40}Ca+^{100}Mo	16 (8,18)	71	22.1	0.15	9
^{36}S+^{104}Pd		71	0.5	0.17	
^{16}O+^{98}Mo	36 (8,20)	110	8.4	0.29	10
^{48}Ti +^{64}Ni		110	5.2	0.05	
^{32}S+^{100}Mo	1.6 ±2.0 (8,21)	117	18.2	0.19	13
^{36}S+^{96}Mo		117	1.7	0.16	
^{32}S+^{100}Mo	18.0 ±2.0 (8,21)	173.5	18.2	0.19	11
^{36}S+^{96}Mo		173.5	1.7	0.16	
^{36}Ar+^{96}Zr	12.0 ±2.0 (8,21)	280	20.6	0.16	14
^{40}Ar+^{92}Zr		280	4.0	0.14	

the relevance of the fusion dynamics.

We must add a couple of comments of interest for the experimental selection of the Dynamical Dipole: i) The centroid is always shifted to lower energies (large deformation of the dinucleus, slightly increasing with impact parameter); ii) A clear angular anisotropy should be present since the prompt mode has a definite axis of

oscillation (on the reaction plane) at variance with the statistical GDR.

In a very recent experiment the prompt dipole radiation has been investigated with a 4π gamma detector. A strong dipole-like photon angular distribution $(\theta_\gamma) = W_0[1 + a_2 P_2(cos\theta_\gamma)]$, θ_γ being the angle between the emitted photon and the beam axis, has been observed, with the a_2 parameter close to -1, see [14]. The deviation from a *pure* dipole form can be interpreted as due to the rotation of the dinucleus symmetry axis vs. the beam axis during the Prompt Dipole Emission. From accurate angular distribution mesurements we can then expect to get a direct information on the Dynamical Dipole Life Time.

At higher beam energies we expect a further decrease of the direct dipole radiation for two main reasons both due to the increasing importance of hard NN collisions: i) a larger fast nucleon emission that will equilibrate the isospin before the collective dipole starts up; ii) a larger damping of the collective mode due to np collisions. This has been observed in ref.[12] and more exps. are planned [14].

The prompt dipole radiation also represents a nice cooling mechanism on the fusion path. It could be a way to pass from a *warm* to a *cold* fusion in the synthesis of heavy elements with a noticeable increase of the *survival* probability, [23],

$$\frac{P_{surv,dipole}}{P_{surv}} = \frac{P_\gamma P_{surv}(E^* - E_\gamma)}{P_{surv}(E^*)} + (1 - P_\gamma) > 1, \frac{P_{surv}(E^* - E_\gamma)}{P_{surv}(E^*)} > 1. \quad (3)$$

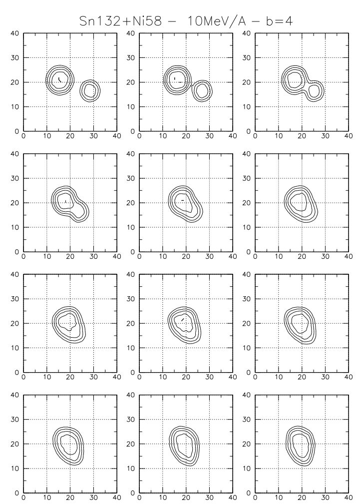

Fig. 4. ^{132}Sn $+^{58}$Ni system ($E = 10AMeV$, $b = 4fm$). Density contour plots (20fm/c time steps)

2.1. *Symmetry Energy Effects*

The use of unstable neutron rich projectiles would largely increase the effect, due to the possibility of larger entrance channel asymmetries. In order to suggest proposals

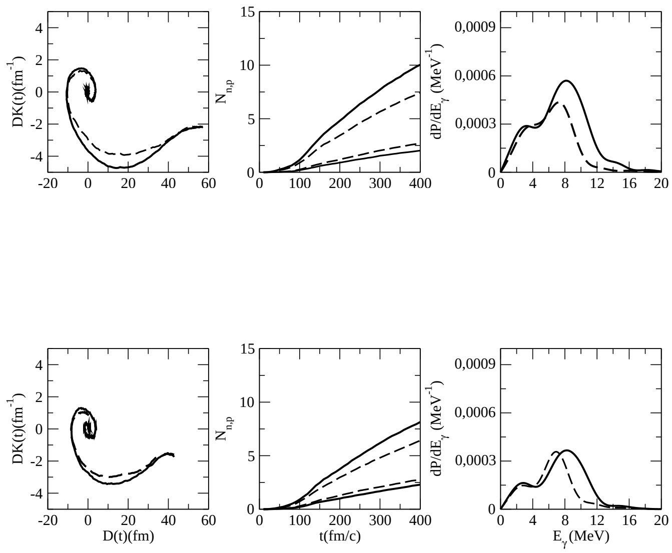

Fig. 5. Upper Curves: ^{132}Sn $+^{58}$Ni system ($E = 10AMeV$, $b = 4fm$). Lower Curves: same reactions but induced by ^{124}Sn. Left Panel: DK-D Spirals. Central panel: neutron (upper) and proton (lower) emissions. Right panel: γ spectrum. Asy-soft (solid lines) and asy-stiff (dashed lines) symmetry energies.

for the new RIB facility $Spiral$ 2, [24] we have studied fusion events in the reaction $^{132}Sn+^{58}Ni$ at $10AMeV$, [25]. We espect a $Monster$ Dynamical Dipole, the initial dipole moment $D(t=0)$ being of the order of 50fm, about two times the larger values of the Table, allowing a detailed study of the symmetry potential, below saturation, responsible of the restoring force of the dipole oscillation and even of the damping, via the fast neutron emission. The corresponding contour plots on the reaction plane are shown in Fig.4. We note the clear rotation of the symmetry axis during the prompt dipole emission.

In the Fig.5 (upper) we present some preliminary very promising results. The larger value of the symmetry energy for the $Asysoft$ choice at low densities, where the prompt dipole oscillation takes place, leads to some clear observable effects: i) Larger Yields, as we see from the larger amplitude of the "Spiral" (left panel) and finally in the spectra (right panel); ii) Larger mean gamma energies, shift of the centroid to higher values in the spectral distribution (right panel); iii) Larger width of the "resonance" (right panel) due to the larger fast neutron emission (central panel). We note the opposite effect of the Asy-stiffness on neutron vs proton emissions. The latter point is important even for the possibility of an independent test just measuring the N/Z of the pre-equilibrium nucleon emission.

The symmetry energy influence can be of the order of 20%, and so well detected. In the lower part of the same figure we present the same results for reactions induced by the stable ^{124}Sn beam. We still se the $Iso-EoS$ effects, but largely reduced.

3. Isospin effects on Deep-Inelastic Collisions

Dissipative semi-peripheral collisions at low energies, including binary and three-body breakings, offer a good opportunity to study phenomena occurring in nuclear matter under extreme conditions with respect to shape, excitation energy, spin and N/Z ratio (isospin). In some cases, due to a combined Coulomb and angular momentum (deformation) effect, some instabilities can show up [26]. This can lead to 3-body breakings, where a light cluster is emitted from the neck region. Three body processes in collisions with exotic beams will allow to investigate how the development of surface (neck-like) instabilities, that would help ternary breakings, is sensitive to the structure of the symmetry term around (below) saturation. In order to suggest proposals for the new RIB facilities, we have studied again the reaction $^{132}Sn +^{64} Ni$ at $10AMeV$ in semicentral events, impact parameters $b = 6, 7, 8fm$, where one observes mostly binary exit channels, but still in presence of large dissipation.

The Wilczynski plots, kinetic energy loss vs. deflection angle, show slightly more dissipative events in the $Asystiff$ case, consistent with the point that in the interaction at lower densities in very neutron-rich matter (the neck region) we have a less repulsive symmetry term. In fact the neck dynamics is rather different in the two cases, as it can be well evidenced looking at the deformation of the PLF/TLF residues. The distribution of the octupole moment over the considered ensemble of events is shown in Fig.6 for the three considered impact parameters.

Except for the most peripheral events, larger deformations, strongly suggesting a final 3-body outcome, are seen in the $Asystiff$ case. Now, due to the lower value of the symmetry enrgy, the neutron-rich neck connecting the two systems survives a longer time leading to very deformed primary fragments, from which eventually small clusters will be dynamically emitted. Finally we expect to see effects of the different interaction times on the charge equilibration mechanism, probed starting from entrance channels with large N/Z asymmetries, like $^{132}Sn(N/Z = 1.64) +^{58} Ni(N/Z = 1.07)$. Moreover the equilibration mechanism is also directly driven by the strenght of the symmetry term.

4. Isospin Dynamics in Neck Fragmentation at Fermi Energies

It is now quite well established that the largest part of the reaction cross section for dissipative collisions at Fermi energies goes through the *Neck Fragmentation* channel, with IMFs directly produced in the interacting zone in semiperipheral collisions on very short time scales [27]. We can predict interesting isospin transport effects for this new fragmentation mechanism since clusters are formed still in a dilute asymmetric matter but always in contact with the regions of the projectile-like and target-like remnants almost at normal densities. Since the difference between local neutron-proton chemical potentials is given by $\mu_n - \mu_p = 4E_{sym}(\rho_3/\rho)$, and the isospin transport is ruled by the density gradient, we expect a larger neutron flow to the neck clusters for a stiffer symmetry energy around saturation, [1,28].

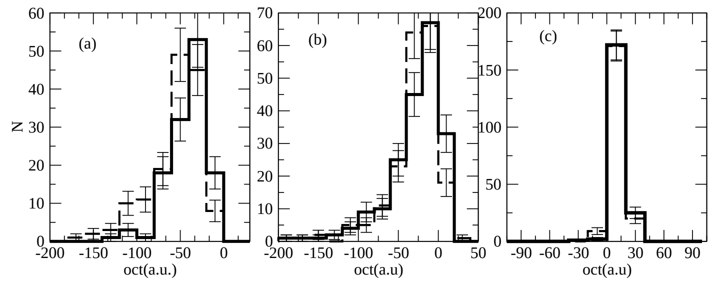

Fig. 6. Distribution of the octupole moment of primary fragments for the $^{132}Sn +^{64} Ni$ reaction at 10 $AMeV$ (impact parameters (a):$b = 6fm$, (b):$7fm$, (c):$8fm$). Solid lines: asysoft. Dashed lines: asystiff

The isospin dynamics can be directly extracted from correlations between N/Z, *alignement* and emission times of the IMFs. The alignment between $PLF-IMF$ and $PLF-TLF$ directions represents a very convincing evidence of the dynamical origin of the mid-rapidity fragments produced on short time scales [29]. The form of the Φ_{plane} distributions (centroid and width) can give a direct information on the fragmentation mechanism [30]. Recent calculations confirm that the light fragments are emitted first, a general feature expected for that rupture mechanism [31]. The same conclusion can be derived from *direct* emission time measurements based on deviations from Viola systematics observed in event-by-event velocity correlations between IMFs and the PLF/TLF residues [29,30,32]. We can figure out a continuous transition from fast produced fragments via neck instabilities to clusters formed in a dynamical fission of the projectile(target) residues up to the evaporated ones (statistical fission). Along this line it would be even possible to disentangle the effects of volume and shape instabilities. A neutron enrichment of the overlap ("neck") region is expected, due to the neutron migration from higher (spectator) to lower (neck) density regions, directly related to the slope of the symmetry energy [31]. A very nice new analysis has been presented on the $Sn+Ni$ data at 35 $AMeV$ by the Chimera Collab., Fig.2 of ref.[33]. A strong correlation between neutron enrichemnt and alignement (when the short emission time selection is enforced) is seen, that can be reproduced only with a stiff behavior of the symmetry energy. *This is the first clear evidence in favor of a relatively large slope (symmetry pressure) around saturation.*

5. Perspectives

We have shown that *violent* collisions of n-rich heavy ions from low to Fermi energies can bring new information on the isovector part of the in-medium interaction, qualitatively different from equilibrium EoS properties, in particular in dilute nuclear

matter. We have presented quantitative results suggesting several isospin-sensitive observables. At low energies we have seen isospin effects on the rather exciting new prompt dipole radiation and on the dissipation in deep inelastic collisions, at Fermi energies the Iso-EoS sensitivity of the isospin transport in fragment reactions.

In conclusion the results presented here appear very promising for the possibility of exciting new results from dissipative collisions with radioactive beams.

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